

## 5

## Building Envelope Performance

Good structural system performance is critical to avoiding injury and minimizing damage to a building and its contents. It does not, however, ensure occupant or building protection. Good performance of the building envelope is also necessary. The envelope includes exterior doors, non-load bearing walls and wall coverings, roof coverings, windows, shutters, and skylights. Historically, poor building envelope performance is the leading cause of damage to buildings and their contents during hurricanes.

### 5.1 Doors

The BPAT observed a limited number of catastrophic door failures. However, in many cases where the doors were weak, the entire wall failed before the door assembly itself failed. Wind-driven water infiltration between the door and frame was a common problem. Most door assemblies observed did not have weatherstripping, and when it was present it provided limited resistance to rain driven by high winds.

Exterior door failure has two important effects. First, failure can cause a sudden increase in internal air pressure, which may lead to exterior wall, roof, interior partition, ceiling, or structural damage. Second, wind can drive water through the opening, causing damage to interior contents and finishes. Essentials to good door performance include: product testing to ensure that sufficient factored strength to resist design wind loads exists; suitable anchoring of the door frame to the building; and for glazed door openings, the use of laminated glass or shutters to protect against windborne missile damage as discussed in Section 5.4. Missiles are both natural and man-made. Natural missiles include tree limbs, and man-made missiles include items such as building debris, fence debris, refuse containers, and lawn furniture.

#### 5.1.1 Glass Doors

A variety of problems with glass doors were observed, including blow-out/blow-in of the door frame and glazing (Figure 5-1), door breakage and loss of glazing from its frame (Figure 5-2), and disengagement of sliding doors from their tracks. These problems were caused by over-pressurization or missile impact.



**FIGURE 5-1** This sliding glass door and window assembly in a hotel room was 7' 2" high and 14' long. The head of the frame was attached with four pairs of #12 or #14 screws in plastic sleeves. The sleeves pulled out and the entire length of the frame was pushed inward, resulting in substantial glass breakage. This building was located on Isla Verde in San Juan.



**FIGURE 5-2** Missiles broke this wood/glass door and several adjacent window panes.

### 5.1.2 Personnel Doors

The BPAT observed few instances of door or door frame failure. However, Figure 5-3 illustrates a metal door that was blown out when the frame anchors pulled out. The door was blown out after the louvered window on the building failed, allowing an increase in internal air pressure.



**FIGURE 5-3** A missile traveling right to left struck the window louver. The door frame was attached by fasteners into wooden plugs that had been set into holes drilled into concrete. Once the louver failed, the door frame failed.

### 5.1.3 Security Grilles, Rolling (Overhead) and Garage Doors

Rolling doors and garage doors frequently perform poorly during high winds. In several instances observed in Puerto Rico, large openings were protected with security grilles, rather than rolling or garage doors (Figure 5-4). Very little load is applied to security grilles during high winds because of the large amount of net free open area. As a result, security grilles performed very well. Depending on the grilles, security grilles may stop large airborne missiles. It is important to note that areas with security grilles must be designed as open structures (without a building envelope). This will normally increase wind pressures acting on the structural frame of the building, as well as components and cladding.



**FIGURE 5-4** The security grille on this fire station offers greater wind performance reliability than a solid door because very little air pressure is applied to it during high winds. This fire station is located on the island of Culebra.

## 5.2 Non-Load Bearing Walls, Wall Coverings, and Soffits

Non-load bearing walls and wall coverings generally performed well during Hurricane Georges. The BPAT did observe several types of problems however.

Non-load bearing walls (or door or window assemblies) that fail can cause extensive interior damage because of the development of high internal air pressure and/or wind-driven water infiltration. Figure 5-5 shows the damage that occurred when a portion of the exterior envelope failed. Composite wall panels and their connections, exterior insulation finish system (EIFS), and other types of exterior wall coverings should be tested to ensure the components have suitable strength.



**FIGURE 5-5** The gypsum wallboard was blown off this interior partition after the exterior non-load bearing wall was blown away, allowing an uncontrolled, rapid increase in internal air pressure.



### 5.2.1 Non-Load Bearing Walls and Soffits

The BPAT observed three types of non-load bearing walls: metal panels over light-gauge steel framing, EIFS, and composite wall panels. Problems resulting in water infiltration were observed with each type and are discussed below.

Metal panels over light-gauge steel framing were the most common non-load bearing walls observed. The BPAT noted the loss of metal panels due to an insufficient number of panel fasteners. In one instance, metal panels at the gable end of a building were damaged when a rooftop water tank blew off and struck the side of the building (Figure 5-6).



**FIGURE 5-6** Rain entered this hospital on Culebra after a water tank struck the metal wall panels.

A problem with EIFS at an ocean front high-rise was also observed. It appeared that the exterior wall stud tracks were insufficiently attached (Figure 5-7). Failure of the wall system resulted in substantial interior damage.

Buildings clad in EIFS often provide a false sense of security since they appear to be clad in concrete, but may or may not be backed by concrete or masonry. When EIFS is used as a covering over concrete, as shown in Figure 5-11, this is not an issue. However, when EIFS is not applied over concrete, as shown in Figure 5-7, the building could be mistakenly construed as offering a safe area of refuge from high winds. EIFS applied on a steel or wood-frame building as the exterior wall is not as reliable a building envelope as a concrete wall in resisting high winds and missiles. An EIFS not backed by concrete or masonry may be identified by a hollow sound when a person bangs on the panel or by a deflection when a person pushes the panel.

The BPAT observed two buildings with composite wall panels composed of thin metal sheets bonded to a cardboard honeycomb core. The panels were attached with screws from the metal framing into the interior metal skin. On one building, the panels were also used as the soffit. In both buildings, the panels blew off because of insufficient strength of the connections between the composite panels and the structural frame of the building (Figure 5-8).



**FIGURE 5-7** This EIFS wall system was composed of synthetic stucco over 1-in thick expanded polystyrene insulation (EPS) over a layer of exterior gypsum board over 6-in deep steel studs, with a layer of gypsum board on the interior side of the studs. Fiberglass batt insulation was installed within the stud cavity. There were several different planes of failure. Insufficiently attached stud tracks appeared to have been the initial failure point. This building was located on Isla Verde.



**FIGURE 5-8** Several composite panels blew off from the fascia and soffit of this building at the airport on Isla Grande. Although several screws were installed, the metal into which they were driven was too thin to develop sufficient blow-off resistance to withstand the wind loads.

### 5.2.2 Wall Coverings

The BPAT observed four types of wall covering problems:

- Loss of stucco applied over cast-in-place concrete.
- Problems with EIFS coverings.
- Ceramic tiles that were blown off.
- Problems caused by wind scour.

None of these problems resulted in water infiltration; however, with the exception of wind scour, failure of the wall covering resulted in additional debris being added into the wind field.

The loss of stucco applied over cast-in-place concrete was the most common problem observed with wall coverings (Figure 5-9). Rather than cast concrete with a relatively flat and smooth surface, traditional practice in Puerto Rico has been to cast the concrete rough, as shown in Figure 5-10, and apply a stucco finish.



**FIGURE 5-9** The stucco was blown off the corner area of this wall, where the suction pressures were high. Note the rough texture of the concrete.





**FIGURE 5-10** This house is under construction. The surface of the concrete is very rough because the plywood form (which is lying down on the ground) was used repeatedly. The rough texture will be compensated for with a stucco surfacing.

While stucco loss had only minor effects to the buildings where it was applied, the windblown debris could have traveled substantial distances and damaged other buildings. This was a particular problem when stucco debris was blown off of tall buildings. Instead of relying on stucco to provide an attractive wall surfacing, the quality of the cast-in-place concrete and CMU construction should be improved so that the concrete or CMU can be left exposed or painted. This would eliminate the missile problems that resulted when stucco was blown away and became airborne.

The BPAT observed an EIFS covering consisting of synthetic stucco applied over two layers of EPS over concrete. There was a superficial bond between the two EPS layers (Figure 5-11). Ceramic tiles were blown off of concrete spandrel panels on a high-rise building (Figure 5-12) and wind scour caused some exterior paint finish damage (Figure 5-13).



**FIGURE 5-11** At this EIFS covering, the synthetic stucco appeared to be well-adhered to the outer EPS layer, but there appeared to be minimal bonding between the two EPS layers. In at least the lower portion of the wall, the first layer was attached with mechanical fasteners deeply recessed into the foam. The delamination occurred near the corner of the building, where the suction pressures were high.



**FIGURE 5-12** A mortar skim coat was applied over the concrete, and the ceramic tiles were set in to the mortar. The primary failure plane was between the mortar and concrete.



**FIGURE 5-13** This house was located on a mountain top that experienced very high wind conditions. The paint scoured off at some of the soffit areas and along the recessed wall.

## 5.3 Roof Coverings

Metal panels and concrete (either exposed or covered with a liquid-applied membrane) were the most common types of roof coverings found on residences. Commercial buildings typically were covered with metal panels or built-up membranes. Several other types of roof coverings were also observed.

Historically, damage to roof coverings is the leading cause of building performance problems during hurricanes. In the rains accompanying a hurricane, water entering the building through damaged roofs can cause major damage to the contents and interior. These damages frequently are more costly than the roof damages themselves.

### 5.3.1 Metal Panels

The BPAT observed a variety of architectural and structural metal panels. Corrugated galvanized steel with exposed fasteners was the most common type found on residences. These panels generally were fastened with smooth- or screw-shank nails (Figure 5-14). With few exceptions, the spacing of fasteners along side laps, eaves, hips, and ridges was insufficient (Figure 5-15).





**FIGURE 5-14** The nail attaching this corrugated metal panel partially backed-out. Screws are much more resistant to back-out. Nail back-out is a problem with metal panel systems because of the large number of load cycles and large amount of deformation the panels can experience during a hurricane. Elsewhere on this roof, some of the panels were blown off.



**FIGURE 5-15** Only a single row of fasteners were installed along the eave and along each side of the ridge. The side laps are insufficiently attached and are lifting in a few areas. The end lap is too far away from the first row of fasteners—another nailer should have been installed. Clips between the joists and wall were retrofitted prior to the hurricane; however, enhanced attachment of the metal roofing was not performed as part of that work. As a result, several of the metal panels were blown off.

In some instances, a framing member was not provided along rake overhangs. Instead, the nailers were simply cantilevered and the metal panels were just attached at each nailer (Figure 5-16). With a continuous rake framing member, as shown in Figure 5-17, the metal panels can be attached with closely-spaced fasteners. Panel fasteners should be closely spaced along the rake because of the extremely high uplift forces that occur in this area during a hurricane.



**FIGURE 5-16** The metal panels along this rake were insufficiently fastened. A framing member was not run up the rake.



**FIGURE 5-17** At this house, a framing member was run up the rake, which allowed the metal panels to be fastened between the nailers (purlins). However, the rake member must have sufficient strength to resist design uplift loads, which does not appear to be the case with this member. Rather than installing a metal edge flashing, these metal panels simply were cantilevered beyond the rake framing, providing a loose edge that is susceptible to lifting and peeling during high winds. Other deficiencies that are noted in this photograph include incorrect nailing of roof material to rake member and inadequately sized and spaced nailers.



Corrugated panels as well as other panel system designs frequently blew off the framing. However, in many instances framing failure caused the panel loss.

In addition to the interior water damage that occurs upon blow-off of metal roof panels, the panels themselves can become high-energy missiles that can damage buildings and other property (Figure 5-18). Metal panels contributed significantly to the amount of debris from Hurricane Georges.



**FIGURE 5-18** Corrugated metal panel wrapped around a power pole.

Many roofs were corroded because their galvanized coating was not very resistant to corrosion. Many were also not field painted. Use of an aluminum-zinc alloy coating (Galvalume) greatly enhances corrosion protection and is particularly beneficial for roofs located near salt water.

### **5.3.2 Exposed Concrete and Liquid-Applied Membranes Over Concrete**

The BPAT observed several cast-in-place concrete roofs with no roof covering. While these roofs provided excellent wind performance, some leaked during the hurricane due to the heavy rains that accompanied the storm (Figure 5-19). Roofs with liquid-applied membranes over the concrete provided excellent performance.



**FIGURE 5-19** This concrete roof deck did not have a roof covering. During the hurricane, water entered the house through the deck. The concrete deck and CMU walls were skimmed with a skim coat of plaster. This house has Miami windows.

### 5.3.3 Tile

While the BPAT observed clay and concrete tile roofs, they make up only a small percentage of steep-slope roofs in Puerto Rico. The BPAT observed many damaged tile roof coverings (Figure 5-20). In some cases, uplift pressure initiated failure while in others it was caused by missile impact.



**FIGURE 5-20** These tiles were heavily damaged, although the wind speed at this location was not very high. As can be seen in the foreground, the roof covering generated a substantial number of missiles. Because of the relatively low wind speed, the tile debris did not travel very far.

Concrete and clay tile roof coverings were vulnerable to missiles. Even when their attachment was well designed and tiles were properly installed, their brittle nature made them especially susceptible to relatively low-energy missiles. Debris from a single damaged tile can impact other roof tiles and lead to a progressive cascading failure. In addition to the roof damage, many high-energy missiles can become airborne.

### 5.3.4 Liquid-Applied Membranes Over Plywood

The BPAT observed only a few liquid-applied membranes over plywood. As long as the roof structure did not fail they provided excellent wind performance (Figure 5-21).



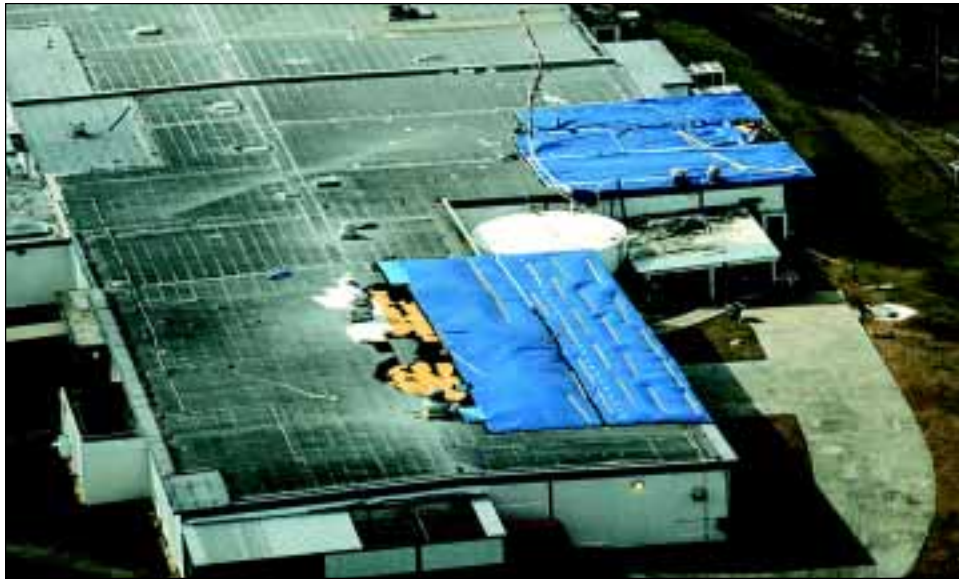
**FIGURE 5-21** This house had a liquid-applied membrane over plywood roof sheathing. This type of roof system typically offered excellent wind performance provided the plywood does not lift. This house was located on the island of Culebra.

### 5.3.5 Built-Up Membranes

Several built-up roofs experienced membrane lifting and peeling. Since these roofs were not generally exposed to very high winds, damage usually was limited to corner areas, rather than complete loss of the roof covering (Figure 5-22).

In at least one instance, aggregate (gravel) from an aggregate surface built-up roof broke a large number of windows down wind (Figure 5-23). As demonstrated again in this hurricane, aggregate from built-up membranes can travel a substantial distance and break glass. On some buildings, tall parapets have been installed to mitigate this type of damage. However, presently there is insufficient guidance available on required parapet height with respect to design wind speed. The double surfacing technique, wherein essentially all of the aggregate is embedded in bitumen, has proven to be a successful means of preventing aggregate blow-off. However, this is a relatively expensive technique. The most conservative approach to this problem is to eliminate the use of aggregate surfacing, but a mineral surface cap sheet, field-applied coating, or an alternative type of roofing system can also be used.





**FIGURE 5-22** This built-up membrane had a mineral surface cap sheet. Because of the roof covering damage, this manufacturing facility on the island of Culebra was shut down for approximately two weeks after the hurricane. This building also experienced roof damage during Hurricane Hugo in 1989.



**FIGURE 5-23** The windows in this building were broken by aggregate from the built-up roof of a nearby building (Figures 5-24 and 5-25).

### 5.3.6 Sprayed Polyurethane Foam

Several sprayed polyurethane foam roofs were observed. They provided excellent wind performance provided the substrate did not lift. Many of them, however, needed to be recoated even before Hurricane Georges occurred. (Recoating is related to long-term roof system performance rather than wind resistance.)

### 5.3.7 Other Roof Coverings

The BPAT observed several other types of roof coverings, including asphalt roll roofing, corrugated asphaltic panels, and asphalt shingles. Since Puerto Rico has so few of these types of roof coverings, detailed observations were not conducted. The performance of asphalt roll roofing and shingles varied.

## 5.4 Windows, Shutters, and Skylights

Several types of window, shutter, and skylight problems were observed with residential and commercial buildings. Some problems were caused by missiles and others by over-pressurization.

Most houses had Miami windows, which are metal jalousie louvers, as shown in Figures 5-16 and 5-19. Since there is no glass in the opening, very high or low internal air pressure can be induced, depending upon wind direction and location of other openings in the building. In addition, these units do not offer much protection against wind-driven rain.

Window and door failure effects are discussed in Section 5.1. Windows are more of a problem than non-glazed doors because they are more susceptible to missile damage. While the probability that any one window will be struck by a missile is small, when it does occur, the consequences can be significant. The probability of missile impact depends upon local wind characteristics and the number of natural and man-made windborne missiles in the vicinity.

Windows can be protected from missile damage by special glazing or exterior shutters. Previous research and testing has shown that if special glazing is used, laminated rather than tempered glass should be specified. Although laminated glass is more easily broken than tempered glass, there is a greater probability that broken laminated glass will stay in the frame (provided the frame detailing is suitable); tempered glass will shatter and fall out of the frame as illustrated by Figures 5-24 and 5-32.

Although shutters are intended to protect glazing from missile impact, most shutter designs do not substantially reduce the wind pressure that is applied to the glazing. Accordingly, glazing protected by shutters should be designed to resist the full positive and negative design wind loads.

Glazing is not typically used with Miami window systems. Therefore, wind loading on buildings with Miami windows should be determined by using ASCE 7-95. This typically results in the building being assessed as partially enclosed (i.e., design for high internal air pressure).



### 5.4.1 Windows

The building in Figure 5-23 had approximately 100 windows broken by aggregate that blew off of a built-up membrane roof across the street. Some panes were tempered glass (Figure 5-24) and others were annealed (Figure 5-25).



**FIGURE 5-24** When these tempered panes broke, they did not produce shards of glass, as did the annealed panes.



**FIGURE 5-25** Although some annealed panes broke into shards, others just broke at the impact point.

The window frame in Figure 5-26 was blown out by over-pressurization of the building interior when the building envelope was breached elsewhere in the building. Missiles broke the glass shown in Figures 5-27 and 5-28. The three buildings in these photos are all located near one another.



**FIGURE 5-26** Half of the window frame blew out. It was attached with two screws in plastic sleeves at the head, three screws at the jamb, and two screws at the sill.



**FIGURE 5-27** One pane in this window was broken by a missile, perhaps from the palm in the foreground.



**FIGURE 5-28** This large window, which was removed and leaned against the wall after the storm, was broken by a missile, most likely a tree limb.

In Figure 5-29, some window frames in this mid-rise building were blown out while in other cases, just the glass was blown out. This appeared to be caused by negative pressure (suction).



**FIGURE 5-29** The glass and frames were blown out at the center room on the top floor. At the room to the right, one of the glass panes was blown out.

The building in Figures 5-30 and 5-31 experienced substantial damage to windows and sliding glass doors. Missiles caused at least part of this damage. The window in Figure 5-32 broke, but since the glass was laminated it did not fragment into separate pieces.



**FIGURE 5-30** Several window and glass door openings broke during the hurricane. They were subsequently covered with plywood (Figure 5-31).



**FIGURE 5-31** High-energy missiles from a nearby building damaged several railings of this building.



**FIGURE 5-32** The broken light in the center is laminated. A sliding glass door located to the left had tempered glass, which was blown out of the frame.

### 5.4.2 Shutters

Many residential and commercial buildings were equipped with shutters of various designs and materials, as shown in Figures 5-33 through 5-39. Problems observed included shutter panel loss, shutter panel displacement (i.e., the panel deflected and pressed against the window), shutter track loss, and blow-out of the window to which the shutter was attached (Figure 5-40). It should be noted that Miami windows look like a type of storm shutter, but offer very little missile protection.





**FIGURE 5-33** A combination of boards and metal panel was used to construct this shutter. Unless shutters are well attached, they can blow off during high winds and become missiles themselves.



**FIGURE 5-34** These windows were equipped with permanent head and sill shutter tracks, which were attached to the wall with closely-spaced fasteners (Figure 5-35).



**FIGURE 5-35** Close-up of Figure 5-34. The steel shutter panels were designed to be locked into the track with wing nuts spaced 6-in on center, a more reliable attachment than that shown in Figure 5-36.



**FIGURE 5-36** Looking up at a shutter panel held in place by clips (a metal wall panel occurs below the shutter track). These clips were spaced 12-in on center. Clips are not as reliable as the bolted attachment shown in Figure 5-35.



**FIGURE 5-37** These windows were equipped with roll-up shutters.



**FIGURE 5-38** This house had hinged plywood shutters. The front shutter protects a Miami window.



**FIGURE 5-39** Steel shutters were used on this mid-rise building, which had a narrow balcony in front of the windows. Since wind speed increases with building height, the shutters on the upper floors can receive very high wind loads. The length of the shutters on this building requires the shutter panels and their connection to the tracks to be strong enough to resist being blown out of the track. The shutter panels also must be stiff enough to prevent deformation against the glass, or they must be set far enough away from the glass so they do not press against it.



**FIGURE 5-40** The window lying on the ground was protected by a shutter. However, the shutter was attached to the window frame. The window frame fasteners were over-stressed and the entire assembly failed. Attachment of the shutter directly to the wall framing is a more reliable method of attachment.



### 5.4.3 Skylights

The BPAT observed a few broken skylights during its investigation. Most were glazed with acrylic sheet. Missiles caused some of the damage. In a large atrium covered with prefabricated translucent panels, many of the skylight panels were blown off.

## 5.5 Seismic Resistance of Nonstructural Elements

The BPAT noted the lack of compression struts, diagonal ties, and perimeter suspension wires in several buildings with acoustical ceilings (Figure 5-41). A lack of bracing was observed on some interior gypsum board/stud partitions as well as inadequate reinforcement and bracing of interior non-load bearing CMU walls (Figure 5-42).



**FIGURE 5-41** Part of the exterior envelope of this building blew away, resulting in damage to the acoustical ceiling. This revealed a lack of seismic resistance of the ceiling system, light fixtures, and ductwork.





**FIGURE 5-42** An interior view of a house under construction (the steel joists are supporting formwork for the concrete slab). The CMU partition is inadequately reinforced and is not supported or laterally braced at the top of the wall.